Electroproduction of π^0 on the Proton near Threshold

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The electroproduction of π^0 on the proton was measured from 0 to 2.5 MeV above threshold for virtual-photon 4-momenta of -0.05 and -0.1 $(\text{GeV}/c)^2$. The sum of the lowest-order contributing multipoles, $a_0 = |E_{0+}|^2 - \epsilon_L |L_{0+}|^2$, was determined with a precision an order of magnitude better than previously possible. Our results for a_0 are consistent with present calculations. Our extracted value for $|L_{0+}|^2$ at the "photon point" is in agreement with recent predictions.

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Pion photoproduction and electroproduction on a nucleon near threshold are of fundamental importance as they are related to basic concepts such as gauge invariance and partially conserved axial-vector currents (PCAC) [1]. One can derive the so-called low-energy theorems (LETs) [2–6], which give model-independent predictions up to low orders in the pion/nucleon mass ratio for the multipole amplitudes that determine the cross sections at threshold [6], i.e., the E_{0+} amplitude for photoproduction as well as E_{0+} and L_{0+} for electroproduction. The recent work of Bernard, Kaiser, and Meissner [7, 8] involving chiral perturbation theory (ChiPT) demonstrates the connection between LETs and low-energy QCD; the ChiPT predictions are based upon QCD and the smallness of up and down quark masses.

It therefore came as a surprise when the analysis of π^0 photoproduction data near threshold on the proton taken at Saclay [9] and Mainz [10] seemed to indicate a value for E_{0+} dramatically different from the LET predictions. One of the principal questions in the interpretation of the photoproduction data was how to incorporate into the LETs the fact that the thresholds for π^0 and π^+ production do not coincide. The present conviction is that LETs should be applied at the corresponding threshold, and that (virtual) charge-exchange contributions are implicitly included in the LET predictions (in the isospin-symmetric case, at least) [11]. Reinterpretation of the $^1\text{H}(\gamma,\pi^0)$ data in this spirit indicates that there is no longer a discrepancy [12,13]. However, a relatively strong and unexpected variation of the E_{0+} amplitude between the π^0 and π^+ thresholds is indicated [12]. By studying electroproduction, we are able to examine the L_{0+} multipole and the dependence of the pion production process on the 4-momentum squared of the virtual photon, q^2.

Recently, Scherer and Koch [6] gave predictions for the $^1\text{H}(e,e'\pi^0)$ multipole amplitudes at threshold. Strictly speaking, their predictions are only valid at threshold and for very small $|q^2| \ll m_\pi^2$. It is very interesting to compare their predictions to experimental results in the limit of $q^2 \to 0$. Bernard, Kaiser, and Meissner [8] have begun to calculate electroproduction amplitudes, but realistic comparisons to data cannot yet be made. The quantity of interest is $a_0 = |E_{0+}|^2 - \epsilon q^2 |L_{0+}|^2 / q_0^{*2}$, where $\epsilon = \left[1 - 2(|\mathbf{q}|^2/q^2)\tan^2(\theta_e/2)\right]^{-1}$ is the photon polarization, with θ_e the angle between the incident and scattered electron, $\mathbf{q}$ the 3-momentum of the virtual photon, and q_0^* the virtual-photon energy in the pion-nucleon frame. Previous electroproduction measurements were characterized by relatively poor resolution in W (≥ 18 MeV), the invariant energy. The cross section increases rapidly with W and for $W > 5$ MeV is dominated by the M_{1+} multipole. Consequently, extracted values for a_0 have large errors.

The purpose of our work is to study the cross section for $^1\text{H}(e,e'\pi^0)$ close to threshold with much higher precision than previously possible. The experiment was performed at The National Institute for Nuclear Physics and High Energy Physics (NIKHEF-K) using the 500-MeV

1% duty factor linear accelerator [14]. Data were taken at an incident electron energy of 500 MeV for $q^2 = -0.05$ and -0.10 $(\text{GeV}/c)^2$ and 350 MeV for $q^2 = -0.05$ $(\text{GeV}/c)^2$. The virtual photon polarization was 0.8 for the 500 MeV $q^2 = -0.05$ point and 0.6 for the other two points. The scattered electrons were detected in the high-resolution quadrupole-dipole-dipole spectrometer. The recoil protons were detected in the large solid angle quadrupole-dipole-quadrupole (QDQ) spectrometer. The overall detection efficiency, determined by measuring elastic *e-p* coincidences from a CH_2 target, ranged from 92% to 98%.

A 10-cm-long, 300-kPa cryogenic gas cell [15] providing a density of 1.5×10^{21} protons/cm^3 at 30 K was used. The effective length of the target as viewed by the spectrometers was determined in three independent fashions: comparing the yield of the gas target to that of a CH_2 target of known thickness, calculating the target length based on previous measurements of the spectrometer acceptances [16], and using the reconstructed target positions of measured events. All three methods provided consistent results within 4%, and yielded effective areal target densities ranging from 3.7×10^{21} to 4.9×10^{21} protons/cm^2, depending on the spectrometer angles.

The analysis of the experimental events coincident within a 80-ns time window included the following steps: discrimination between π^+ and p events using the scintillator information from the QDQ focal-plane detector; reconstruction of the momentum and angles at the target of the scattered electron and proton using known optical properties of the spectrometers [17, 18] (the optical properties were checked during the experiment using sieve slit measurements [17]); correction of the timing for flight-time differences in the spectrometers, resulting in a typical time resolution for the real coincidence events of 3 ns FWHM; and reconstruction of the missing mass in the reaction, which yielded a peak at the π^0 mass with typical 2 MeV FWHM.

In the raw data stream the accidental rate was typically 3 orders of magnitude greater than the real rate, as a result of the $\sim 1\%$ duty-factor beam and the high instantaneous luminosity of about $10^{38}/(\text{cm}^2/\text{s})$. The application of the various cuts in particle identification, target position, scattering angles, corrected coincidence time, and missing mass resulted in an invariant energy spectrum which, after subtraction of random coincidences, is consistent with zero below threshold and clearly nonzero above threshold (Fig. 1). The resolution in W is better than 0.5 MeV. This enabled us to accurately determine the cross section close to threshold.

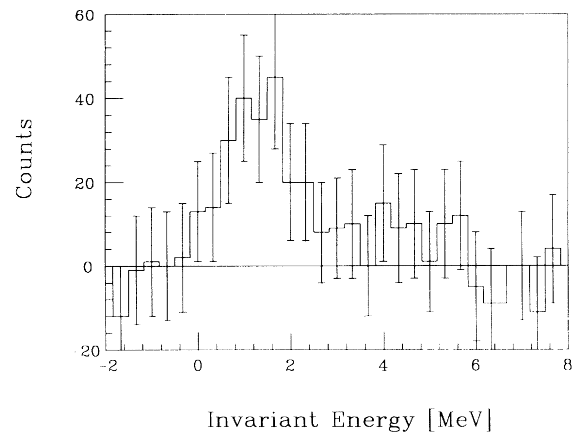

FIG. 1. Invariant-energy histogram (with accidentals subtracted) showing the rapid rise from zero at threshold. The zero of the abscissa corresponds to threshold for π^0 production. The decrease above 1.5 MeV is due to the limited acceptance of the spectrometers.

Near threshold, recoiling protons are boosted along the momentum transfer vector, and emerge within a small cone around it. Up to 1.5 MeV above threshold for $q^2 = -0.05$ $(\text{GeV}/c)^2$ and up to 2.5 MeV above threshold for $q^2 = -0.1$ $(\text{GeV}/c)^2$ the proton cone fits in the angular acceptance of the proton spectrometer. Hence in these W ranges we obtained a 4π solid angle acceptance (in the center of mass) for π^0 production by detecting the proton.

The measured cross section integrated over all pion angles can be written

$$\frac{d^3\sigma}{d\Omega_e\, dE_e} = 4\pi \frac{\Gamma p_\pi^*}{q_L} \frac{W}{m_p} \left\{ a_0 + b p_\pi^{*2} \right\} ,$$

where Γ is the virtual-photon flux factor, q_L is the equivalent real photon energy, p_π^* is the pion 3-momentum in the pion-nucleon frame, and bp_π^{*2} represents the p-wave contribution which must be subtracted in order to determine a_0. The value of b has been determined by Brauel *et al.* [19] with a precision of about 25%. Since the bp_π^{*2} term contributes 14% at most, the uncertainty in the

TABLE I. Summary of our experimental data. Where errors are stated, the first is statistical and the second systematic.

q^2 $(\text{GeV}/c)^2$	ϵ	$d^3\sigma/d\Omega_e\, dE_e$ (nb)	a_0 (μb)
-0.044	0.58	$0.43 \pm 0.11 \pm 0.02$	$0.185 \pm 0.059 \pm 0.010$
-0.050	0.79	$1.88 \pm 0.38 \pm 0.09$	$0.391 \pm 0.089 \pm 0.022$
-0.100	0.62	$0.60 \pm 0.11 \pm 0.03$	$0.353 \pm 0.084 \pm 0.022$

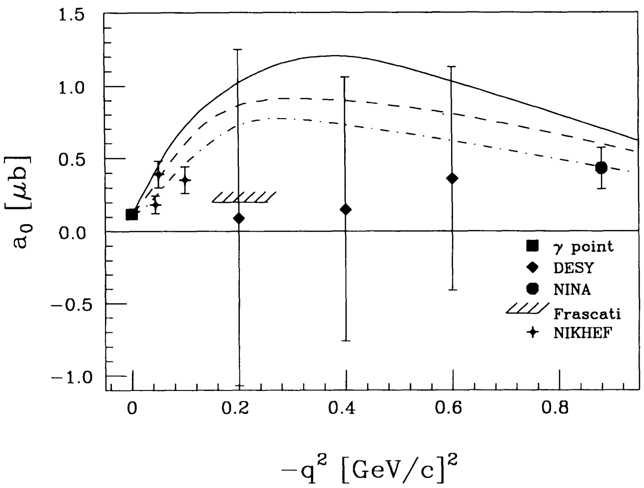

FIG. 2. Plot of the world's data for a_0 and some theoretical predictions. The solid curve is due to Ref. [20], the dashed curve is due to [22], while the dot-dashed curve is due to [21]. The data are from [19, 28, 29] and the present work, while the photon point is the LET prediction of 0.11 μb [6]. It should be noted that all the curves are calculated for $\epsilon = 1$ and roughly scale with ϵ. The previous data are for $\epsilon \geq 0.9$, while our data are for $\epsilon = 0.6$ and $\epsilon = 0.79$.

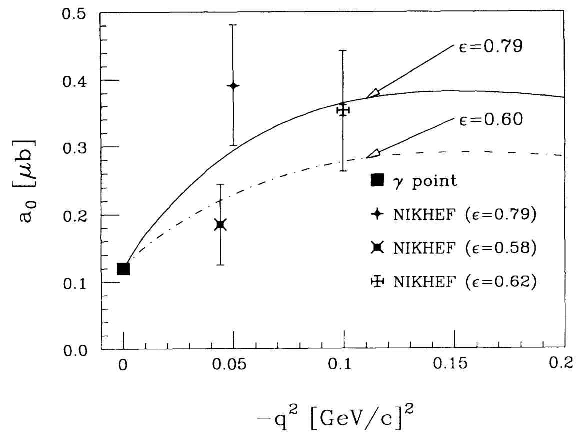

FIG. 3. Plot of our data for a_0 and calculated curves from Vainshtein and Zakharov [23]. Again we stress that the data points cannot be compared directly since they are for different ϵ's.

value of b barely influences our uncertainty in a_0.

The measured cross section is an average over the considered region in W and the acceptances of the spectrometers. The variation of the values over the acceptances as well as the corresponding volume element $d\Omega_e\, dE_e$ were taken into account by Monte Carlo calculations in the determination of our final values for a_0, which are given in Table I.

Figure 2 displays the world's data including our results. The marked increase in precision, which is due to the fact that we were able to measure near threshold with high resolution in the invariant energy, is clearly seen. The theoretical predictions of Devenish and Lyth [20], which are based on a parametrization of nonthreshold data, as well as those of Dombey and Read [21] and Benfatto [22], which are based upon extensions of LETs, are globally consistent with our results.

Figure 3 shows our results with the truncated Born series presented by Vainshtein and Zakharov [23]. Here we show the explicit dependence of ϵ in the Born series. It is clearly seen that the Born series adequately describes our data.

Using a complete Born series [24] we calculated the relative contributions to a_0 of the L_{0+} and E_{0+} multipoles shown in Fig. 4. It is seen that in the region of our experimental values the E_{0+} multipole goes to zero, so the dominant contribution is due to L_{0+} at both $q^2 = -0.05$ and -0.10 (GeV/c)^2. Assuming the E_{0+} contribution to a_0 is given by the complete Born series for our data, we can linearly extrapolate to $q^2 = 0$ and find a value for $|L_{0+}|^2$ at the photon point of 0.13 ± 0.05 μb, which is in good agreement with the prediction of Scherer and Koch [6] of 0.16 μb, and of Bernard, Kaiser, and Meissner of 0.2 μb [25]. By assuming $|E_{0+}|^2 = 0$ we obtain a measure of the model dependence of our extrapolation. For $|E_{0+}|^2 = 0$ we obtain $|L_{0+}|^2 = 0.145 \pm 0.05$ μb, showing a model dependence error of ± 0.015 μb.

In summary, as a result of our good energy and angle resolution we have been able to determine the cross section for the $^1\mathrm{H}(e, e'p)\pi^0$ reaction near threshold with much higher precision than previously possible. Our measured values are in global agreement with present theoretical predictions. A further increase in precision is required for detailed tests of theoretical predictions near threshold. Proposals for further studies of near threshold

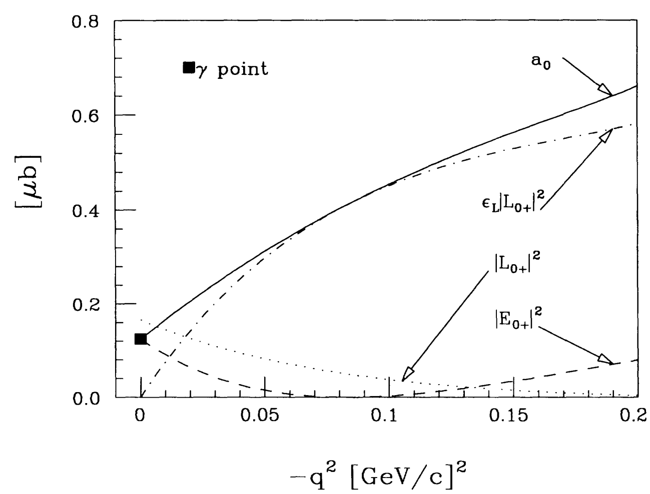

FIG. 4. Comparison of the longitudinal and transverse contributions to a_0. The solid curve is for a_0 calculated using a complete Born series. The other curves give the separate E_{0+} and L_{0+} contributions. All the curves are calculated for $\epsilon = 0.79$ and $\epsilon_L = \epsilon q^2/q_0^{*2}$.

π^0 electroproduction on the proton have been approved at Bates [26] and NIKHEF-K [27].

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